LABORATORY Spotlight
The National High Magnetic Field Laboratory
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NHMFL Hybrid Magnet is Again at 45 T!

On February 1, 2001, the NHMFL Hybrid Magnet was returned to user service at 45.1 T after nearly seven months of operation at reduced field strength.

The first user to operate at 45 T DC was John Singleton of Oxford University. The experiment examined the magnetoresistance of the prototype layered organic superconductor κ-(BEDT-TTF)$_2$Cu(NCS)$_2$ (Fig. 1). There has been vigorous debate in the scientific community about the nature of the superconductivity in this material and whether the interlayer electrical transport is coherent or incoherent.

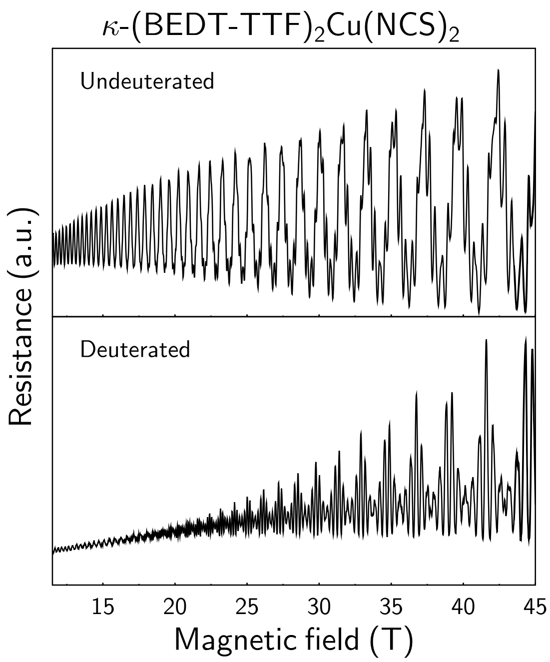
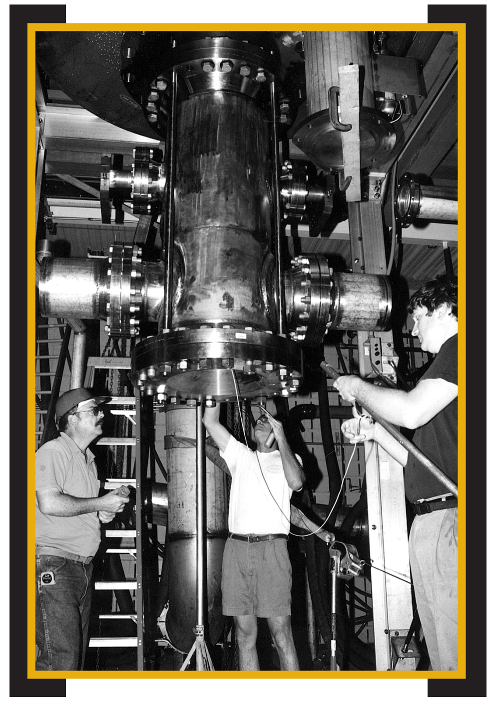


Figure 1. Magnetoresistance of κ-(BEDT-TTF)$_2$Cu(NCS)$_2$ versus applied magnetic field.

Singleton *et al.* used the Hybrid Magnet to exceed the upper critical magnetic field of 35 T in their sample. Using a two-axis rotation probe, they measured the normal state magnetoresistance as a function of magnetic field orientation. The appearance of a peak in the magnetoresistance when the magnetic field lies parallel to the sample layers is a very strong indication that the Fermi surface of this material is three dimensional and that the electrical transport between the layers is coherent.

Fig. 2 shows the magnetoresistance at 42 T, as a function of polar angle, θ, at two azimuthal orientations, Φ. The coherence peak is visible close to θ=0 degrees; conventional angle-dependent magnetoresistance oscillations can be seen on either side.



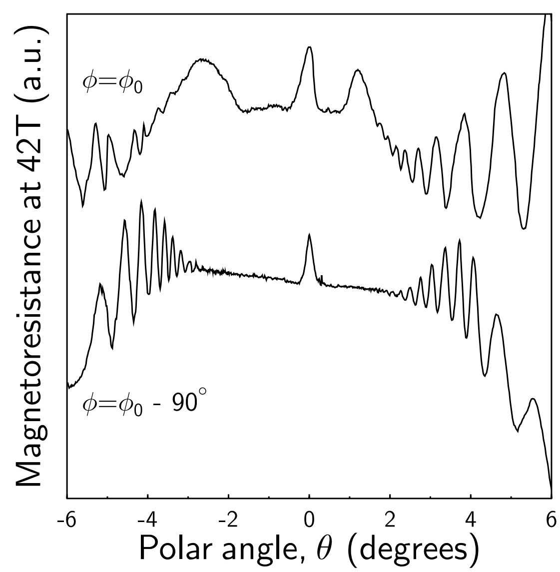


Figure 2. Magnetoresistance of κ-(BEDT-TTF)$_2$Cu(NCS)$_2$ versus polar angle.

The NHMFL Hybrid is the highest field DC magnet in the world and the only facility in which this experiment could be performed. The Hybrid consists of two sets of coils: the superconducting outsert and the resistive insert. The outsert contains three concentric cable-in-conduit coils operating at 1.8 K. The resistive insert contains five water-cooled Florida-Bitter coils. The system was originally designed for the outsert to provide 14.2 T with 30.8 T coming from the insert for a total of 45.0 T.

On July 7, 2000, the superconducting outsert was damaged during an unprotected quench. Since that time, it has been operating at 80% of its design field, i.e., 11.4 T. In December 2000, an upgrade of the resistive insert was completed that allowed operation of the insert at sufficiently high field to overcome the shortfall from the outsert, i.e., 33.7 T. On February 1 and 2, 2001 the combined system was operated to 45.1 T for a total of 13 full field sweeps over a nine-hour period. This accomplishment makes the magnet not only the highest field DC magnet in the world, but the insert by itself is the highest field resistive magnet in the world.

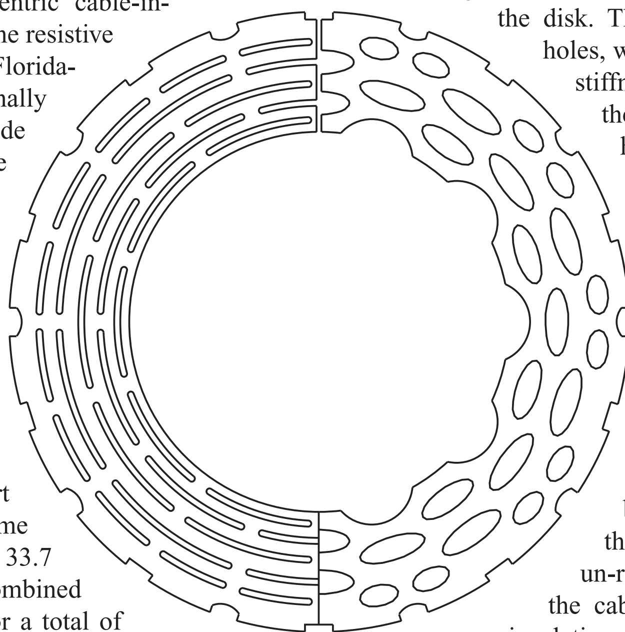


Figure 3. Cooling hole patterns of Florida-Bitter disks of innermost coil of hybrid insert. Left side is mid-plane hole pattern: long slender holes maximixe hoop strength. Right side is end-turn pattern: shorter, broader holes maximize in-plane bending stiffness.

The upgrade of the resistive insert constitutes a substantial advance in high field resistive magnet design. Traditionally, high field resistive magnet designers have focused on the stress state at the mid-plane of the magnet, and ignored end effects. It was argued that since the field is a maximum at the mid-plane, the stress must be a maximum at the mid-plane. If one examines the stress in a hybrid insert carefully, one sees that the discontinuity of the helical structure coupled with the lack of magnetic clamping at the end of the coil can lead to a large in-plane bending of the end disks. Consequently, hybrid inserts have frequently been limited by disk bending at the ends of the coils rather than hoop tension at the mid-plane. To address this problem, it has been common practice at various laboratories to use thicker turns at the ends of the coils than the mid-plane.

The recent upgrade to the NHMFL Hybrid is the first time magnet designers have considered the stress state at the mid-plane and ends separately and used disks with different cooling hole patterns at different points in the coil to best accommodate the local stress state. Fig. 3 shows the cooling hole pattern used at the mid-plane and ends of the innermost coil of the hybrid insert. The mid-plane cooling hole pattern uses very long slender holes to maximize the hoop strength of the disk. The end turns use shorter, broader holes, which results in an in-plane bending stiffness nearly 30 times greater than at the mid-plane. By varying the cooling hole pattern along the length of the coil, we are able to provide a coil with a more uniform stress state and higher operating field: perhaps 48 to 50 T at some future date.

Per the NSF's mandate, the NHMFL intends to repair the superconducting outsert by replacing the damaged *A* coil. This repair project will be led by John Miller and will require the following steps: (1) procuring un-reacted Nb_3Sn cable, (2) installing the cable in a stainless steel jacket, (3) insulating the jacketed conductor with glass tape, (4) winding the jacketed conductor into a coil, (5) heat treating the coil to form the Nb_3Sn superconductor, (6) making terminals, (7) disassembling the existing outsert, (8) installing the new coil, and (9) testing. The plan is to perform tasks two through nine in-house. The project is intended to take about three years, assuming funding is available.

Until the new super-conducting *A* coil is ready for installation, the Hybrid will be available to the user community at 45 T. Additional improvements to the insert are presently underway to further enhance the end turn stiffness of the coils, thereby increasing the lifetime at these increased currents and fields. After the outsert has been replaced, we intend to push the combined system toward 50 T by making additional minor improvements to the resistive insert. The Hybrid is expected to have annual maintenance shutdowns lasting a few months. The 2001 shutdown is scheduled from February 5 until May 28.

This article was contributed by Mark Bird, Arzhang Ardavan, Hans Schneider-Muntau, and John Miller. For more information, contact Mark Bird via e-mail (bird@magnet.fsu.edu).